Genie

Overview of version 3 major release

Marco Roda
mroda@liverpool.ac.uk
marco@genie-mc.org

on behalf of GENIE collaboration

University of Liverpool

16 October 2018
NuInt - GSSI
L'Aquila

Neutrino MC generators: our vision

- Connect neutrino fluxes and observables
  - event topologies and kinematics
- *Good* generators
  - optimal coverage of physics processes
  - Uncertainty validation
  - Tune the *physics* models
- Specific requirements for *experiments*
  - fast enough for MC analyses
  - being able to prove the validity of a configuration

  $\Rightarrow$ Simple models can be perfectly acceptable

Neutrino MC generators: our vision

- Connect neutrino fluxes and observables
  - event topologies and kinematics
- *Good* generators
  - optimal coverage of physics processes
  - Uncertainty validation
  - Tune the *physics* models
- Specific requirements for *experiments*
  - fast enough for MC analyses
  - being able to prove the validity of a configuration
  - $\Rightarrow$ Simple models can be perfectly acceptable

$\Rightarrow$ Tuning is difficult - CPU time

- $\Rightarrow$ Unprecedented systematic tuning program

We don't believe in a *perfect theory* approach

- There are always things that need to be derived from measurements

$\Rightarrow$ Dealing with errors is unavoidable

Roles of generators in oscillation physics

- Compare data and models
  - Reliability and validity region
  - $\Rightarrow$ You cannot study oscillations without fully understood models
- Compare dataset against dataset
  - Data quality and data sources are increasing $\Rightarrow$ tensions
  - $\Rightarrow$ joint analyses
  - $\Rightarrow$ comparing results from different experiments
- Global fits
  - A generator is the ideal place for global fits
    - Controls the model implementation
  - Finding the best parameters
  - Cross Section priors based on data
- Feedback for experiments
  - Drive the format of cross section releases
  - Hint toward key measurements

GENIE - www.genie-mc.org

GENIE Collaboration

Luis Alvarez Ruso[8], Costas Andreopoulos[2,5], Christopher Barry[2], Francis Bench[2], Steve Dennis[2], Steve Dytman[3], Hugh Gallagher[7], Steven Gardiner[1], Walter Giele[1], Robert Hatcher[1], Libo Jiang[3], Rhiannon Jones[2], Igor Kakorin[4], Konstantin Kuzmin[4], Anselmo Meregaglia[6], Donna Naples[3], Vadim Naumov[4] Gabriel Perdue[1], Marco Roda[2], Jeremy Wolcott[7], Júlia Tena Vidal[2], Julia Yarba[1]

[Faculty, Postdocs, PhD students]

1 - Fermi National Accelerator Laboratory, 2 - University of Liverpool, 3 - University of Pittsburgh, 4 - JINR Dubna,

5 - STFC Rutherford Appleton Laboratory, 6 - CENBG Université de Bordeaux, 7 - Tufts University, 8 - Valencia University

Core GENIE mission - from GENIE by-law

Framework "... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community ..."

Universality "... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales ..."

Global fit "... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes ..."

Status overview

- Well established generator
  - Used by many experiments around the world
  - Fermilab experiments are driving the momentum
    - Lot of interest from LAr experiments
- Two main efforts
  - Model development
    - Mostly happen during the latest releases of GENIE v2
    - growing interest from theorists wanting to supply new models
  - Tuning
    - ⇒ Entering the tuning phase
- The new release v3
  - Interface with the developments
  - ⇒ Tunes against public datasets
  - ⇒ Easy way to share configurations
    - Experiments can propose their own configuration for others to use

Models

- Steady introduction as alternate models
- Many thanks to all who contributed
  - more detailed list in backup
- List of most interesting physics introduction:
  - Valencia complete QE+MEC+LFG model
  - Berger-Sehgal resonance model+MiniBooNE form factors
  - Berger-Sehgal coherent model + updated Rein-Sehgal coherent
  - Single kaon production of *Athar et al.*
  - New cascade FSI model with medium corrections for pions and nucleons

  $\Rightarrow$ See Libo's talk

A complete generation needs more than a set of models

- The experimental smearing mixes all the different interaction process
- There are ad-hoc solutions in every generator that needs tuning

  $\Rightarrow$ Transition between RES and DIS interactions

  $\Rightarrow$ See Júlia's talk

Database and validation

- Comparing GENIE predictions against public datasets
  - Modern Neutrino Cross Section measurement
    - nuclear targets
    - MiniBooNE, T2K, MINERvA
  - Historical Neutrino Cross Section Measurement
  - Measurements of neutrino-induced hadronic system characteristics
    - e.g. Forward/backward hadronic multiplicity distributions
  - Measurements of hadron-nucleon and hadron-nucleus event characteristics
    - FSI tuning
    - For pion, kaons, nucleons and several nuclear targets
    - Spanning hadron kinetic energies from few tens MeV to few GeV
  - Semi-inclusive electron scattering data
    - electron-nucleus QE data
    - electron-proton resonance data

$\Rightarrow$ Validation based on neutrino, electron and hadron beams simulations

- We are not limited to simulate only neutrinos

GENIE Version 3

graphics by `grafiche.testi@gmail.com`

- Interface with the work behind the scenes

⇒ "Comprehensive Model Configurations"

- Self-consistent collections of primary process models
- Help cooperation between collaborations
  - Unified model identifications
- single command-line flag
  - `--tune G18_02a_00_000`
- Complete characterisation against public data
- Possibility to host configurations provided by experiments

- Access to tunes against datasets
  - same interface
  - Documentation:
    - Manual
    - Dedicated web page – tunes.genie-mc.org/

Comprehensive Model Configurations

- CMC of interest
  - G18_01a and G18_01b - Default + MEC
    - with Empirical MEC
    - CCQE process is Llewellyn Smith Model
    - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
    - Nuclear model: Fermi Gas Model - Bodek, Ritchie
    - Inclusion of diffractive and Lambda production models
  - G18_02a and G18_02b - Improved pion production models
    - Similar to G18_01a and G18_01b
    - Berger-Sehgal for resonant interaction
    - Berger-Sehgal for coherent interaction
  - G18_10a/b and G18_10i/j - Theory based model
    - Nieves' MEC
    - CCQE process is Nieves
    - Dipole Axial Form Factor (a/b) - Depending on $M_A = 0.99\ GeV$
    - Z-expansion (i/j)
    - Nuclear model: Local Fermi Gas Model
  - G00_00a - Historic Default
    - now deprecated
- Dark matter ⇒ GDM18_00a
- Low energy ⇒ GVLE18_01a

Technical updates

- New Git Repository - `https://github.com/GENIE-MC`
  - Contributions are welcome through this new channel
  - Thanks to HEPForge for the many years of support
- Reweight is now a detached and independent repository
- Website - `http://www.genie-mc.org/`
- Updated manual hosted on a dedicated DocDB
- Code
  - System handles multiple configurations
  - Updated XML file structure ⇒ safer and with no redundancies
  - Files re-organisation

Tuning

- Why tuning?
  - Constraint parameters
  - Provide specific tunes for experiments
    - Liquid Argon tune
- Expected Output:
  - Parameter sets from data from various experiments
  - with estimated systematic errors
    - Parameter covariance matrix
    - ⇒ No official support until v4
- Numerical methodology
  - Old problem in High Energy Physics
    - CPU demanding
  - Solution found in the Professor suite
    - `http://professor.hepforge.org`
  - Numerical assistant
    - Developed for ATLAS experiment

Professor

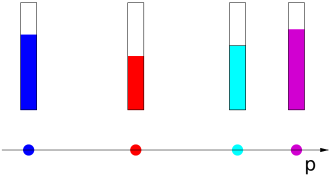
- Parameterisation instead of a full MC

Professor

- Parameterisation instead of a full MC
  1. Select points of param space

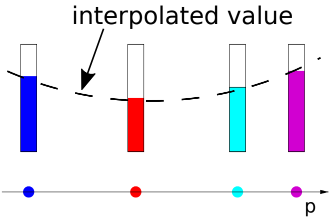
Professor

- Parameterisation instead of a full MC
  1. Select points of param space
  2. Evaluate bin's behaviour with brute force



Professor

- Parameterisation instead of a full MC
  1. Select points of param space
  2. Evaluate bin's behaviour with brute force
  3. Parameterisation $I(p)$

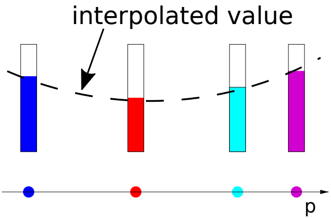


Professor

- Parameterisation instead of a full MC
  1. Select points of param space
  2. Evaluate bin's behaviour with brute force
  3. Parameterisation $I(p)$
  - Repeat for each bin
- a parameterization $I_j(p)$ for each bin
  - N dimension polynomial
  - Including all the correlation terms up to the order of the polynomial

$\Rightarrow$ Minimise according to $\vec{I}(p)$

- $\sim$ 20 parameters
  - This limit is due to disk space requirements
  - It can be overcome
- Special thanks to H. Schulz



Advantages and expectations

- All parameters can be tuned
  - Not only reweight-able
  - ⇒ no dedicated machinery to develop
- Advanced features
  - Take into account correlations
  - weights specific for each bin and/or dataset
    - Proper treatment while handling multiple datasets
    - Restrict the fit to particular subsets
  - Priors can be included
  - Nuisance parameters can be inserted
    - proper treatment for datasets without correlations
    - ⇒ MiniBooNE, old bubble chamber datasets

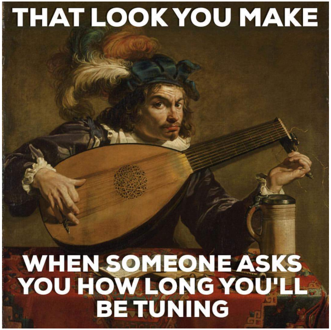
- Professor based Reweight package in development
  - Reweight hard to maintain: each model requires a specific reweight module
  - Better interface with the errors produced by a global fit
  - Allow non-reweightable parameters - e.g. HN FSI
  - ⇒ version 4

Next steps

- Tuning program
  - hadronization retune
    - Pythia 6 and 8 (implementation is ongoing)
  - Tune of FSI
    - Both hN and hA intranuke
  - Free nucleon cross section model
    - ⇒ Julia's talk about RES/DIS transition region
- Data from liquid argon experiments
  - Part of GENIE collaboration is in SBND
  - Plan for argon tunes
- Paper in preparation
- Official code deployed
  - Finalizing the web page for the validation plots

Conclusion

- GENIE has improved
  - New models
  - Systematic validation against Cross section data
  - Maintained and rich database
- We have a very powerful fitting machinery
  - Validated with many tunes
  - A new branch of analyses
  - Alternative tool to propagate systematic uncertainties
- Researchers are encouraged to contact us to start a collaboration
  - New theory models
  - New experimental collaborations



Backup slides

Production version **v2.10.0** - New physics models

- Bodek-Christy-Coopersmith eff. spectral function (EPJC 74:3091, 2014).
  B. Coopersmith and A. Bodek (Rochester)
- Very-High Energy extension (up to 5 TeV, working towards PeV scales)
  K. Hoshina (Wisconsin)
- Inclusive η production.
  J. Liu (W&M)
- Berger-Sehgal resonance model (PRD 76, 113004, 2007)
  J. Nowak (Lancaster) and S. Dytman (Pitt)
- Kuzmin-Lyubushkin-Naumov resonance model (MPL A19, 2815, 2004)
  J. Nowak (Lancaster), I. Kakorin (JINR) and S. Dytman (Pitt)
- Improved INTRANUKE/hA FSI model.
  S. Dytman and N. Geary (Pitt)
- Single K model by Alam, Simo, Athar, and Vacas (PRD 82, 033001, 2010).
  C. Marshall (Rochester) and M. Nirkko (Bern)

Production version **v2.12.0** - New physics models

- Bhattacharya, Hill, and Paz QE Z expansion model (PRD 84:073006)
  A. Meyer (Chicago)
- Local Fermi Gas & Nieves-Amaro-Valverde CCQE with RPA (Phys. Rev. C70, 055503 (2004); Phys. Rev. C72:019902, 2005)
  J. Johnston and S. Dytman (Pitt)
- Updates to the GENIE hown-grown empirical 2p-2h model
  S.Dytman (Pitt)
- Valencia 2p-2h model (Phys.Rev. D88:113007, 2013)
  J. Schwehr (CSU), D.Cherdack (CSU) and R. Gran (UMD)
- Berger-Sehgal coherent π production (PRD 79:053003, 2009)
  G. Perdue (Fermilab), H. Gallagher (Tufts), D. Cherdack (CSU)
- Alvarez Ruso, Geng, Hirenzaki and Vacas microscopic coherent pion production (PRC 75:055501, 2007; PRC 76:068501, 2007)
  D.Scully, S. Dennis and S. Boyd (Warwick)

Production version **v2.12.0** - New physics models

- Oset, Salcedo and Strottman FSI model (Phys. Lett. B 165:13, 1985; Nucl. Phys. A 468:631, 1987.)
  T. Golan (Fermilab and Rochester)
- Kaon FSI improvements
  F. de Maria Blaszczyk (LSU), S. Dytman (Pitt)
- Pais QE Hyperon production model (Ann. Phys. 63:361, 1971)
  J. Poage and H. Gallagher (Tufts)
- Updated Rein diffractive pion model (Nucl.Phys. B278:61, 1986).
  J.Wolcott (Tufts)
- Several resonance model updates.
  L.Jiang (Pittsburgh) and I.Kakorin (JINR & ITEP)
- Kuzmin, Naumov energy-dependent axial-mass model.
  I.Kakorin (JINR & ITEP)

Other notable changes in **v2.10.0** / **v2.12.0**

- Upgrade of nucleon decay generator in GENIE.
  M.Sorel (IFIC)
- Simulation of $n - \bar{n}$ oscillations.
  J. Hewes and G. Karagiorgi (Manchester)
- New Honda, Athar, Kajita, Kasahara and Midorikawa (HAKKM) atm. ν flux (PLB718:1375, 2013) driver added to existing FLUKA and BGLRS ones.
  G.Majumder, A.Ajmi (INO Collab.); T.Katori (QMUL)
- A new *unified* event generation app for all Fermilab experiments (in the NuMI, Booster and LBNF beamlines) and updates in the flux drivers.
  R.Hatcher (Fermilab)
- Event reweighting I/O
  J.Yarba (Fermilab)
- New GSL (GNU Scientific Library) dependency
  S.Dennis (Warwick/Liverpool)
- "ROOT6 and C++11"-ready!
  S.Dennis (Warwick/Liverpool)
- LHAPDFv5 dependence now optional; CERNLIB/PDFLIB discontinued.
  S.Dennis (Warwick/Liverpool)

+ Bug fixes. For a detailed list see: `https://releases.genie-mc.org`

GENIE Version 2.12.8

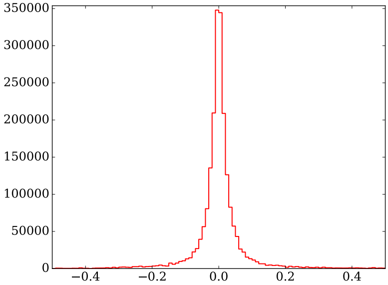
- CCQE models
  - Llewellyn Smith
  - Nieves, Amaro and Valverde
- MEC models
  - Empirical
  - Nieves Simo Vacas
- Nuclear Models
  - Relativistic Fermi Gas
  - Local Fermi Gas
  - Effective Spectral Functions

- Single Kaon
- Λ production

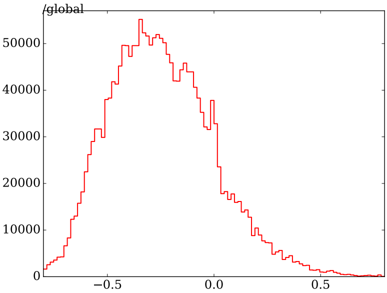
- RES
  - Rein-Sehgal
  - Berger-Sehgal
  - Kuzmin-Lyubushkin-Naumov
- COH
  - Rein-Sehgal
  - Berger-Sehgal
  - Alvarez Ruso
- FSI - Intranuke
  - Full Intra-Nuclear cascade
  - Schematic based on Hadron-nucleus data

- Only one Comprehensive Model Configuration (CMC)
- Default tune has not changed

Parametrization residuals



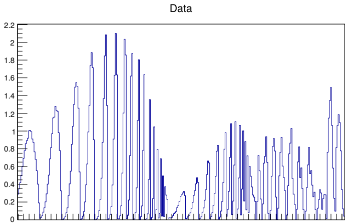
Good



Bad

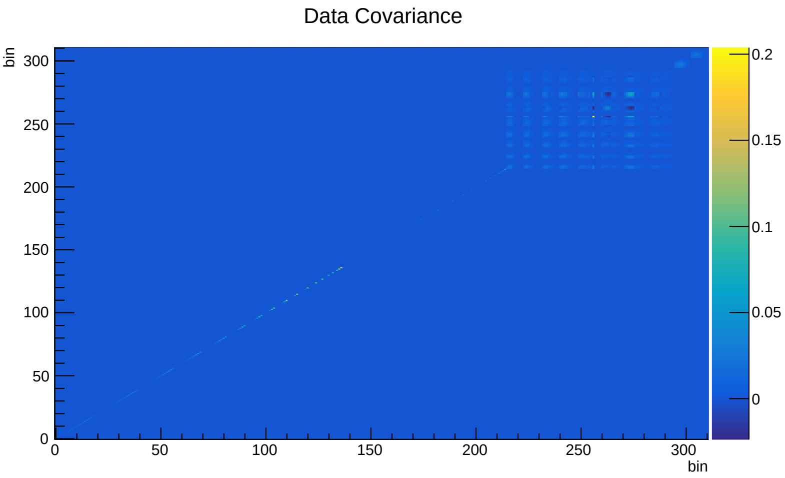
Datasets - 311 data points

- MiniBooNE ν_μ CCQE
  - 2D histogram
  - 137 points
  - No correlation matrix
- MiniBooNE $\bar{\nu}_\mu$ CCQE
  - 2D histogram
  - 78 points
  - No correlation matrix
- T2K ND280 0π (2016) V2
  - 2D histogram
  - 80 points
  - full covariance matrix
- MINERvA ν_μ CCQE
  - 1D histogram
  - 8 points
  - full covariance matrix
- MINERvA $\bar{\nu}_\mu$ CCQE
  - 1D histogram
  - 8 points
  - full covariance matrix



- Missing Covariance between Neutrino and antineutrino data
  - Minerva released this information!

Data covariance

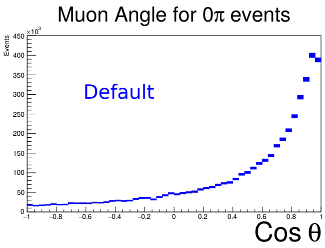


Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance

Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance

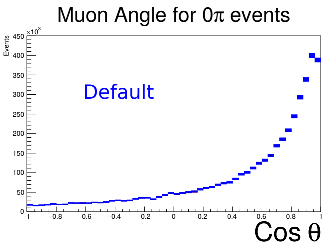


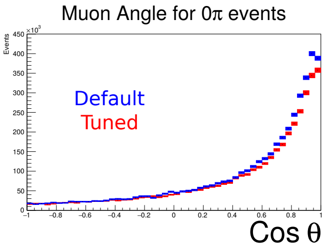
- Data Constraints for Oscillation analyses

Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance

- Data Constraints for Oscillation analyses
  - Propagate the result to other observables

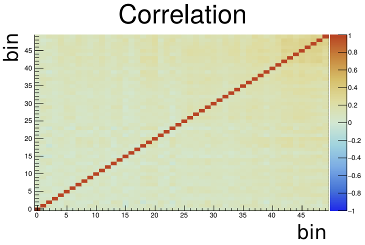


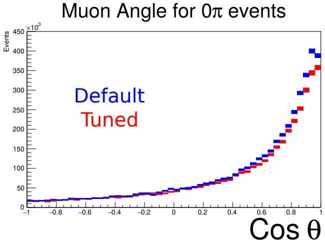


Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance

- Data Constraints for Oscillation analyses
  - Propagate the result to other observables
- Propagate parameters uncertainty through the parameterization





Model comparison

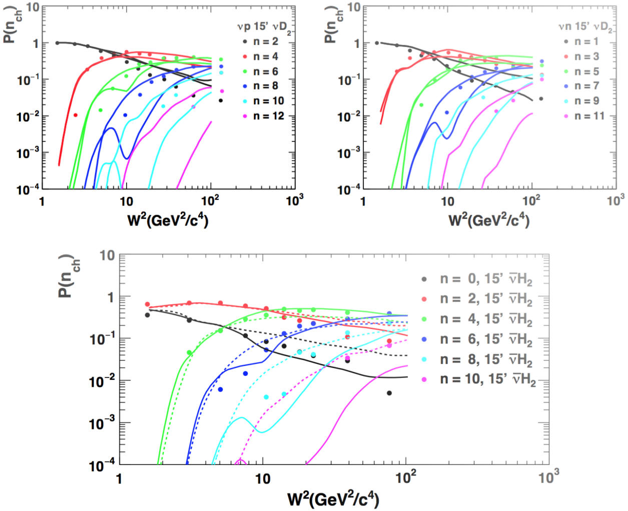
Model comparison

Martini et al. Nieves et al. Amaro et al. Lovato et al. Bodek et al.

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2} k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}\,G_E^2\,R_\tau + \frac{\omega^2}{q^2}\,G_A^2\,R_{\sigma\tau(L)} + \right.$$
$$\left. +\;2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\,\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\,\frac{\epsilon+\epsilon'}{M_N}\,\tan^2\frac{\theta}{2}\,G_A\,G_M\,R_{\sigma\tau(T)}\right]$$

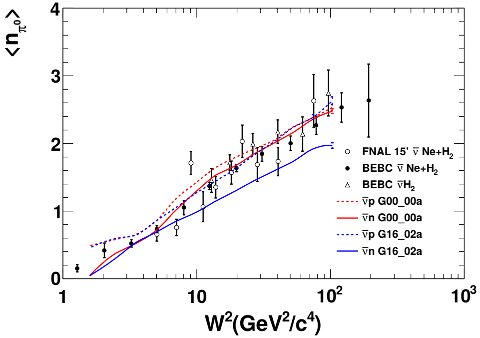
[M.Martini, FUNFACT JLab workshop]

Hadronization example

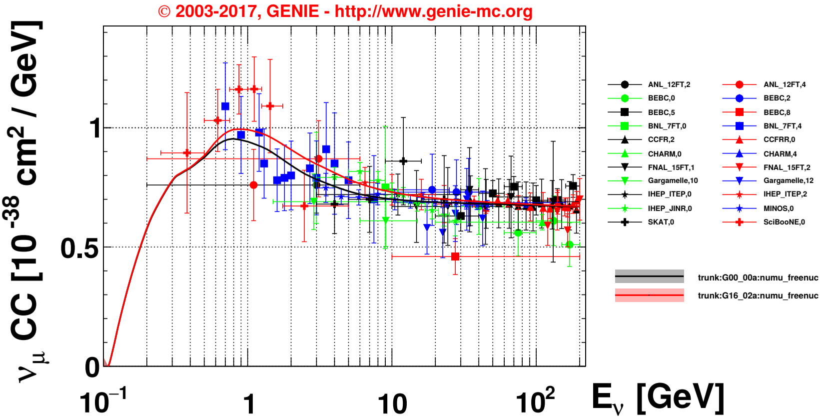


Hadronization example

Hadronization example



Evolving datasets - Old datasets

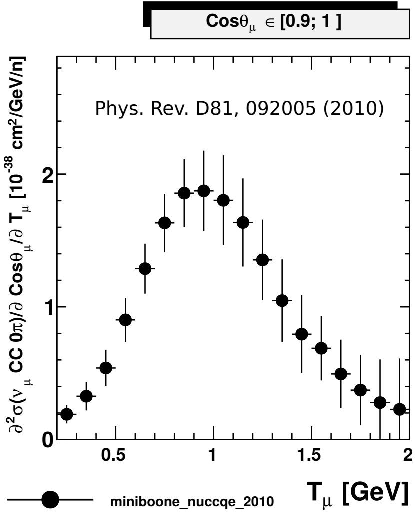


- Functions of E_ν
- “Only” statistical errors

- Ignore nuclear effects
- Poor statistical interpretation
- Poor model discrimination power

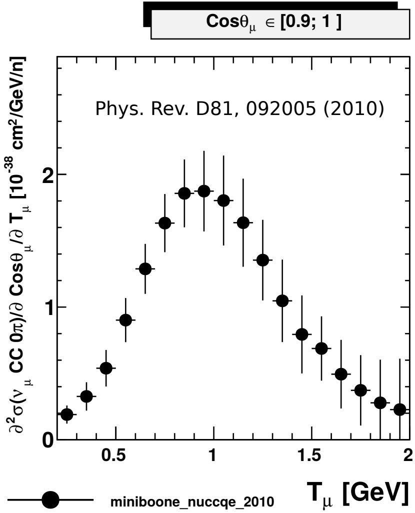
Evolving datasets - Present datasets

- Functions of experimental observables
- flux-integrated
- Usually differential cross-sections
  - 1D, 2D
- Organized by topology, not process
- Higher statistics
- More statistically robust
  - ⇒ See Fermilab neutrino seminar by Mikael Kuusela - 2017/04/13



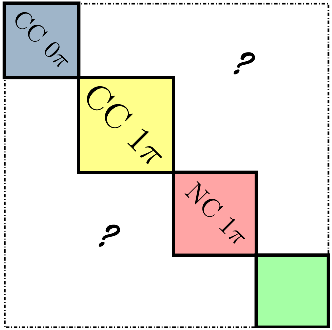
Evolving datasets - Present datasets

- Functions of experimental observables
- flux-integrated
- Usually differential cross-sections
  - 1D, 2D
- Organized by topology, not process
- Higher statistics
- More statistically robust
  - ⇒ See Fermilab neutrino seminar by Mikael Kuusela - 2017/04/13
- Sometimes incomplete
- Helped the development of new models
  - 2p/2h



Future of datasets - a personal view

- One big covariance matrix per experiment
- Correlation between datasets
- Differential cross sections, dim > 2
- No data releases with this format
  - SBND is thinking about a solution
- It is usually a big effort but ...
  - dedicated experiments



We finally have a way to use these datsets

- Statistically coherent
- Complete error analysis

The Comparisons

The GENIE suite contains a package devoted to comparing GENIE predictions against publicly released datasets.

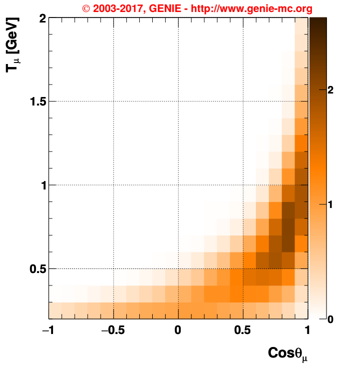
- Provides the opportunity to improve and develop GENIE models
- Crucial database for **new GENIE global fit** to neutrino scattering data
- All sorts of possible formats and dimensions
- Can store correlations, even between different datasets

The database

- **Modern Neutrino Cross Section measurement**
  - nuclear targets
  - typically flux-integrated differential cross-sections
  - MiniBooNE, T2K, MINERvA
- **Historical Neutrino Cross Section Measurement**
  - Bubble chamber experiment
- Measurements of neutrino-induced **hadronic system characteristics**
  - Forward/backward hadronic multiplicity distributions
  - Multiplicity correlations
  - ...
- Measurements of **hadron-nucleon and hadron-nucleus event** characteristics (for FSI tuning)
  - For pion, Kaons, nucleons and several nuclear targets
  - Spanning hadron kinetic energies from few tens MeV to few GeV
- Semi-inclusive **electron scattering data**
  - electron-nucleus QE data
  - electron-proton resonance data

MiniBooNE CCQE

- Both ν and $\bar{\nu}$
  - Phys. Rev. D81, 092005 (2010)
  - Phys. Rev. D88, 032001 (2013)
- Double differential cross section
- flux integrated
- No correlations
- Preferred model is Nieves Model (G16_02a)
  - excellent agreement for ν
  - $\chi^2 = 101/137$ DoF
- worse for $\bar{\nu}$
  - $\chi^2 = 176/78$ DoF

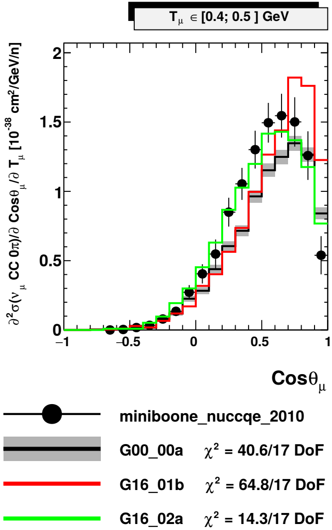


$\partial^2\sigma(\nu_\mu$ CC $0\pi)/\partial \text{Cos}\theta_\mu/\partial T_\mu$ [10^{-38} cm^2/GeV/n]

Data: miniboone_nuccqe_2010

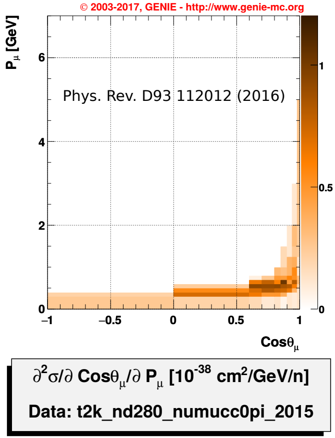
MiniBooNE CCQE

- Both ν and $\bar{\nu}$
  - Phys. Rev. D81, 092005 (2010)
  - Phys. Rev. D88, 032001 (2013)
- Double differential cross section
- flux integrated
- No correlations
- Preferred model is Nieves Model (G16_02a)
  - excellent agreement for ν
  - $\chi^2 = 101/137$ DoF
- worse for $\bar{\nu}$
  - $\chi^2 = 176/78$ DoF



T2K ND280 0π

- Double differential cross section
- flux integrated
- Fully correlated
- Tensions between datasets
- Preferred model is G16_01b
  - $\chi^2 = 135/67$ DoF
- all models look reasonable "By eye" estimation
  - correlation is complicated
  - We can't ignore it!



T2K ND280 0π

- Double differential cross section
- flux integrated
- Fully correlated
- Tensions between datasets
- Preferred model is G16_01b
  - $\chi^2 = 135/67$ DoF
- all models look reasonable "By eye" estimation
  - correlation is complicated
  - We can't ignore it!